FINAL REPORT

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Scientific Officer: Dr. Yapa Rajapakse

Principal Investigator: C. Fong Shih

Address: Division of Engineering, Brown University, Providence, RI 02912

Significant Results on Compressive Failure by Kinking

Using a video microscope equipped with microscope lens, we have recorded various stages of kink band formation and band width broadening in unidirectional fiber composites. These deformation modes are different from the commonly assumed kinematics employed by many investigators. The in-situ video pictures show that the early stage of kink band formation involves progressive, cooperative fiber bending/rotation and plastic shearing of the matrix within a shallow narrow band of about 10 fiber diameters wide. This deformation mode causes geometric softening of the material within the band. At some point in this process, fiber rotation within the kink band is halted. The termination of fiber rotation, referred to as fiber lock-up, is believed to be brought about by the stiffening of the composite shearing response at large shear strains. This forces the kink band to spread into the unkinked material (which is soft in shear) by band width broadening to accomodate the continuous overall end-shortening of the specimen. In the band broadening stage, the bends in the fiber (at the edges of the kink band) propagate into the unkinked material much like a pair of dislocations moving away from one another. Band widths of 30 to 50 fiber diameters with a steeper inclination than the initial band orientation have been observed. The final width of the kink band is set when the fibers snap. The mechanism of band broadening bears some similarity to neck propagation in certain polymers often termed 'cold drawing'.

Based on our observations and theoretical studies, we presented arguments for two design approaches. The first is based on the peak stress and the second uses steady-state kinking stress [25, 26] as illustrated in the accompanying figure and text on page 5.

Publications supported by Grant:

[1] "Mechanics of Dynamic Debonding" (with W. Yang and Z. Suo) Proceedings of the Royal Society, Series A, Vol. 433, pp. 679-697 (1991).

[2] "Cracks on Bimaterial Interfaces: Elasticity and Plasticity Aspects," Materials Science and Engineering, A143, pp. 77-90 (1991).

[3] "Elastic-Plastic Analysis of Cracks on Bimaterial Interfaces: Part III - Large Scale Yielding," (with R. J. Asaro and N. P. O'Dowd), Journal of Applied Mechanics, Vol 58, pp. 450-463 (1991).

[4] "Ductile Failure of a Constrained Metal Foil," (with A. G. Varias and Z. Suo), Journal of the Mechanics and Physics of Solids, Vol. 39, pp. 963-986 (1991).

[5] "Family of Crack-Tip Fields Characterized by a Triaxiality Parameter: Part I - Structure of Fields," (with N. P. O'Dowd), Journal of the Mechanics and Physics of Solids, Vol. 39, pp. 983-1015 (1991).

[6] "Combined Mode I - Mode II and Mode I - Mode III Fracture of Brittle Materials" (with S. Suresh) Scripta Metallurgica et Materialia, Vol. 25, pp. 991-996 (1991).

[7] "Mixed-Mode Inelastic Crack-Tip Fields" Homogeneous Solids and Bimaterial Interfaces" (with S. Suresh) Scripta Metallurgica et Materialia, Vol. 25, pp. 1017-

[8] "Corner Singularities of Three-Dimensional Planar Interface Cracks," (with F. Ghahremani), Journal of Applied Mechanics, Vol. 59, pp. 61-68 (1992).

[9] "Elastic-Plastic Analysis of Combined Mode I, II and III Crack-Tip Fields under Small-Scale Yielding Conditions," (with J. Pan), International Journal of Solids and Structures. Vol. 29, pp. 2795-2184 (1992).

[10] "Crack Extension and Kinking in Laminates and Bicrystals," (with T-C. Wang and Z. Suo), International Journal of Solids and Structures, Vol. 29, pp. 327-344 (1992).

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[13] "Family of Crack-Tip Fields Characterized by a Triaxiality Parameter: Part II - Fracture Applications" (with N. P. O'Dowd) Journal of the Mechanics and Physics of Solids, Vol. 40, pp. 939-963 (1992).

[14] "Higher-Order Analysis of Crack-Tip Fields in Elastic Power-Law Hardening Materials" (with L. Xia and T.C. Wang), *Journal of the Mechanics and Physics of Solids,]* Vol. 41, pp. 665-687 (1993)

[15] "Continuum and Micromechanics Treatment of Constraint in Fracture" (with R. H. Dodds, Jr. and T. L. Anderson), *International Journal of Fracture]*, Vol. 64, pp. 101-133 (1993).

[16] "Crack Growth Along-Bi-Material Interfaces Under Monotonic and Cyclic Loading," (with S. Suresh), in Mis-Matching of Welds, ESIS 17 (edited by K.-H. Schwalbe and M. Kocak) Mechanical Engineering Publications, London, pp. 3-17 (1994).

[17] "An Interface Crack Between an Orthotropic Thin Film and Substrate," (with Y. Xu and J. A. Blume), *International Journal of Fracture*, Vol. 63, pp. 369-381 (1993).

[18] "Kink Band Formation and Band Broadening in Fiber Composites Under Compressive Loading," (with P. M. Moran and X. H. Liu) *Acta Metallurgica et. Materialia*, Vol. 43, pp. 2943-2958 (1995).

[19] "The Mechanics of Compressive Kinking in Ductile Matrix Fiber Composites" (with X.H. Liu and P.M. Moran), Composites Engineering (1995). To appear.

[20] "Quasi-Static Crack Advance Under a Range of Constraints – Steady-State Fields Based on a Characteristic Length," (with A.G. Varias) *Journal of the Mechanics and Physics of Solids,* Vol. 41, pp. 835-861 (1993).

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[22] "Dynamic Steady Crack Growth in Elastic-Plastic Solids – Propagation of Strong Discontinuities," (with A.G. Varias), *Journal of the Mechanics and Physics of Solids,* Vol. 42, pp. 1817- 1848, (1994).

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[25] "Kink Band Formation and Band Broadening in Fiber Composites Under Compressive Loading," (with P. M. Moran and X. H. Liu) *Acta Metallurgica et. Materialia*, Vol. 43, pp. 2943-2958 (1995).

[26] "The Mechanics of Compressive Kinking in Ductile Matrix Fiber Composites" (with X.H. Liu and P.M. Moran), Composites Engineering (1995). To appear.

[27] "Notch Sensitivity of Fiber-Reinforced Ceramics" (P. Gu), *International Journal of Fracture*, Vol. 70, pp. 253-266 (1995).

Books (and sections thereof)

[1] "Models for Metal/Ceramic Interface Fracture" (with Z. Suo), Chapter 12 in *Fundamentals of Metal-Matrix Composites,* eds. S. Suresh, A. Mortensen and A. Needleman Butterworth-Heinemann, pp. 217-232 (1993).

Graduate Assistants Supported by Grant and their Status

[1] A. Varias, (Thesis submitted in September, 1990), May 1991, Ph.D.

[2] P. Mchugh, (Thesis submitted in August, 1991), May 1992, Ph.D.

[3] N. O'Dowd, (Thesis submitted in September, 1991), May 1992, Ph.D.

[4] Pei Gu, (Thesis submitted in September, 1993), May 1994, Ph.D.

[5] Peter Moran, research assistant working towards Ph. D degree, started on project in September 1993.

[6] Xiao-Hu Liu, research assistant working towards Ph. D degree, started on project in September 1993.

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KINK BAND FORMATION AND BAND BROADENING IN FIBER COMPOSITES UNDER COMPRESSIVE LOADING

P. M. MORAN, X. H. LIU and C. F. SHIH

Division of Engineering, Brown University, 182 Hope Street, Providence, RI 02912, U.S.A.

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Abstract—Various stages of kink band formation, propagation and band width broadening were recorded by a high resolution video camera. Based on these observations, the easiest modes of deformation have been identified and these form the basis of a new kinematic model for kinking. Theoretical predictions for kink band orientation and compression strength under steady-state band broadening are made. The conditions at incipient kinking and the incipient kinking stress are investigated. The relevance of the incipient kinking stress and the band broadening stress are discussed.

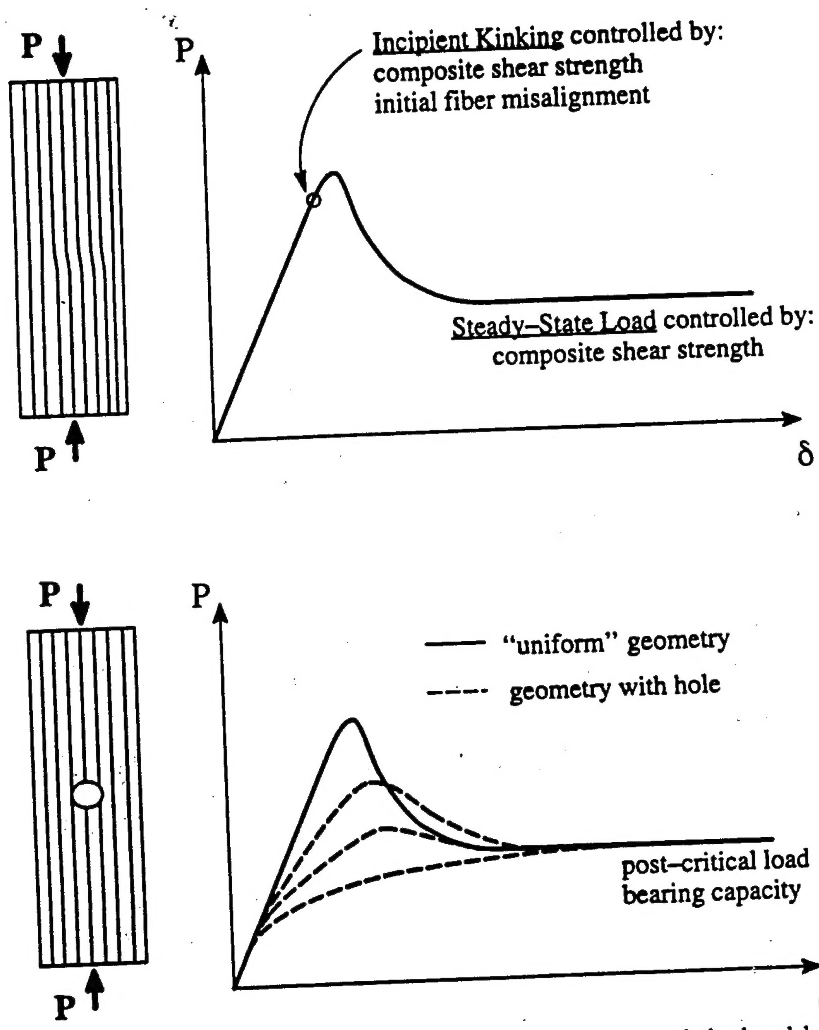

Fig. 7. Response of a "uniform specimen"; the incipient kinking stress and the band broadening stress are indicated. In specimens containing large geometric imperfections, the nominal peak stress drops significantly and can be expected to approach the stress associated with band broadening.